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ORIGINAL ARTICLE

Evaluation of Skills in Arthroscopic Training Based on Trajectory and Force Data

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Abstract Objective evaluation of surgical skills is essential for an arthroscopic training system. We asked whether a quantitative assessment of arthroscopic skills using scores, time to completion, instrument tip trajectory data, and force data was valid. We presumed more experienced surgeons would perform better on a simulated arthroscopic procedure than novices, therefore validating the quantitative assessment. Surgical trainees ($n = 12$), orthopaedic residents ($n = 12$), and experienced arthroscopic surgeons ($n = 6$) were tested on a Sawbones® knee simulator. Subjects performed a joint inspection and probing task and a partial meniscectomy task. The trajectory data were measured using an electromagnetic motion tracking system and the force data were measured using a force sensor. The experienced group performed both tasks with higher scores and more quickly than the less experienced groups. The path length of the probe and the scissors was substantially shorter and the probe velocity was considerably faster in the experienced group. The trainee group applied substantially stronger forces to the joint during the joint inspection and probing task. Our data suggest a performance assessment using an electromagnetic motion tracking system and a force sensor provides an objective means of evaluating surgical skills in an arthroscopic training system.

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Introduction

Arthroscopic surgery has become more common among patients and orthopaedic surgeons in recent years. This surgical technique offers benefits of less trauma, reduced pain, and quick recovery for patients. Diagnostic accuracy and therapeutic efficacy are major characteristics of this technique. However, arthroscopic procedures demand highly developed psychomotor skills, because observation of the field is limited and the ability to manipulate instruments is less than in traditional open surgery. Surgeons must be able to perceive a three-dimensional environment from a two-dimensional camera image and handle the equipment skillfully. Therefore, it is important for arthroscopic trainees to improve their surgical skills and understand their skill levels objectively to safely and effectively perform arthroscopic surgery.

Arthroscopic training and skill assessment with cadavers, animals, or direct observation are limited because of ethical restrictions and low availability [3, 10, 16]. Therefore, numerous investigators have developed virtual reality simulators for arthroscopy [1, 2, 4, 6, 8, 9, 12, 15]. A knee arthroscopy instructional course has been available at the Kyushu University Training Center for Minimally Invasive Surgery since 2005. A critical challenge for surgical education is to objectively evaluate the skill levels of surgical trainees [2, 8, 9, 12, 15]. Assessing the instrument tip trajectory reportedly is useful in training for laparoscopic surgery [5, 11]. Measurement with a force and torque sensor is similarly useful to evaluate skills in endoscopic sinus surgery and laparoscopic surgery training [13, 14, 19].

We asked whether quantitative evaluation using these scores (ie, the score representing the number of figures touched in the time limit in a joint inspection and probing task, and the scores from a partial meniscectomy task), time to completion, instrument tip trajectory data, and force data would be useful to distinguish levels of skill in arthroscopic surgery. We hypothesized more experienced surgeons would have better motor performance in a simulated arthroscopic procedure than individuals with less experience with the technique.

Materials and Methods

We identified three groups of volunteers with different stages of arthroscopic skills. Group 1 consisted of surgical trainees who had observed but had not performed any arthroscopies (n = 12), Group 2 consisted of orthopaedic residents with 10 to 20 cases of actual arthroscopic operations (n = 12), and Group 3 were experienced arthroscopic surgeons (n = 6). All performed two kinds of simulated arthroscopic tasks. Quantitative data of scores, time to completion, instrument tip trajectory, and surgical force were obtained and differences among the three groups were examined. The parameters with a difference in accordance with the surgical skills were regarded to be valid in distinguishing levels of arthroscopic surgical skills. A power analysis was performed based on the path length data of the arthroscope in our preliminary research (a difference in the mean = 2200 mm, the standard deviation = 1500 mm, significant level = 0.05, and power = 0.80) to indicate a sample size of 9.7 in each group could address the questions.

We used an electromagnetic motion tracking system to measure the path length and velocity of the arthroscope and probe and scissors. The Aurora measurement system (Northern Digital Inc, Waterloo, Canada) is designed to calculate the position and orientation of sensor coils (Fig. 1). The field generator creates an electromagnetic field with a characterized volume of 500 mm × 500 mm × 500 mm. Sensor coils react to the electromagnetic field and produce signals. The sensor interface unit transmits the signals to the system control unit. The system control unit calculates the position and orientation of the sensor coils based on these data and communicates the results to the host computer. The system can determine five degrees of freedom for each sensor coil tool except the rotation around the sensor coil's z-axis. It has a maximum measurement rate of 45 Hz if measured with five or less sensor coils. In this experiment, we attached the sensor coils to the shaft of the operative instrument.

Fig. 1 An electromagnetic measurement system is shown. The field generator creates a measurement volume of 500 mm × 500 mm × 500 mm. Sensor coils are attached to the surgical instrument.

We used a force analysis system to estimate the degree of surgical forces administered during operative procedures. The six degrees of freedom force sensor (Nitta Co, Osaka, Japan) provides three force measurements along three orthogonal axes and three torque measurements along the same axes. It is connected to an interface unit, which consists of an analog-to-digital converter and an amplifier. This interface unit is connected to the host computer. The sensor detects values (forces F_x, F_y, F_z; torques M_x, M_y, M_z) concurrently with a sampling frequency of 8 kHz and outputs the data set every 125 µs. We fixed the force sensor beneath the knee model in the training center (Fig. 2). Zero point adjustment can be completed in approximately 5 seconds before the measurement. Once surgical forces are loaded on the joint model, the output of the force sensor is digitized and recorded by the host computer and then shown in real time on a computer display. We used only the data sets of three forces in this study because the load center of surgical force, which was located in front of the origin of coordinates, varied according to each procedure.

After orientation and 5 minutes of practice, subjects performed two kinds of tasks designed to assess the core psychomotor skills needed in arthroscopy. The tasks were

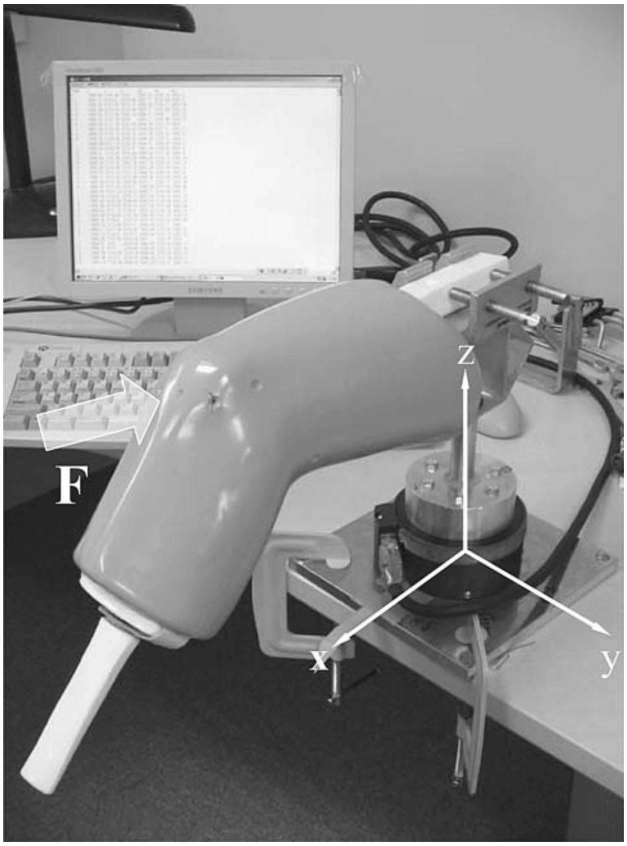

Fig. 2 A six degrees of freedom force sensor is fixed beneath the knee model. This sensor detects surgical forces loaded on the joint, providing the data set of forces F_x, F_y, and F_z and torques M_x, M_y, and M_z.

performed using the Sawbones® knee simulator (Pacific Research Laboratories Inc, Vashon, WA). Task 1 was a joint inspection and probing task. Subjects handled the scope and probe to touch the figures located variously in the joint. A total of 10 figures were placed. This task was limited to 5 minutes. Task 2 was a partial meniscectomy task. The amount of meniscus to be removed was indicated with a line in advance and subjects performed the resection along the line. An excessive resection was indicated with a red line. Task 2 had a limit of 6 minutes. The score in Task 1 was the number of figures touched within the time limit. Scores in Task 2 were graded as excellent, good, fair, or poor for each skill regarding the adequacy of the amount and smoothness of the margin in resection. The computer calculated the following parameters: time to complete each task, trajectory data of the tip of the surgical instruments, and force data. We assessed three indices of force exerted: (1) peak value; (2) average value; and (3) integration of the absolute values.

To determine the differences in the continuous variables (such as scores in Task 1, time to completion, instrument tip trajectory data, and force data) among the three groups, we used a one-way factorial ANOVA with Fisher's protected least significant difference post hoc test. Differences in the discrete variables (scores in Task 2) among the three groups were determined by the Kruskal-Wallis test, Mann-Whitney U test, and Bonferroni correction. Differences in the motor performance on a simulated arthroscopic procedure, in accordance with subjects' surgical skills, was regarded as validation of the quantitative evaluation method.

Results

The expert group obtained better scores ($p = 0.014$) than the resident group, and the resident group obtained better scores ($p = 0.003$) than the trainee group in Task 1 (Table 1). In Task 2, the expert and the resident groups

Table 1. Results of Task 1

Parameter	Group 1 12	Group 2 12	p Value	Group 3 6	p Value
Score	2.5 ± 2.6	6.3 ± 3.6	$0.003^{*,\ddagger}$	10 ± 0	$0.000^{**,\ddagger}$; $0.014^{\dagger,\ddagger}$
Time (seconds)	300 ± 0	287.8 ± 22.9	0.292^{*}	198.8 ± 54.8	$0.000^{**,\ddagger}$; $0.000^{\dagger\ddagger}$
Path length of the scope (mm)	7978 ± 2604	6348 ± 1239	$0.043^{*,\ddagger}$	3815 ± 912	$0.000^{**,\ddagger}$; $0.012^{\dagger,\ddagger}$
Velocity of the scope (mm/second)	26.6 ± 8.7	22.2 ± 4.7	0.111^{*}	21.5 ± 4.7	0.130^{**}; $0.828^{\dagger}$
Path length of the probe (mm)	1262 ± 442	996 ± 420	0.109^{*}	485 ± 134	$0.001^{**,\ddagger}$; $0.015^{\dagger,\ddagger}$
Velocity of the probe (mm/second)	13.6 ± 9.5	18.1 ± 8.5	0.201^{*}	27.1 ± 4.1	$0.003^{**,\ddagger}$; $0.040^{\dagger,\ddagger}$
Peak force (N)	15.6 ± 6.2	18.2 ± 8.7	0.366^{*}	11.7 ± 4.3	0.279^{**}; $0.074^{\dagger}$
Average force (N)	3.4 ± 1.0	3.3 ± 1.1	0.652^{*}	2.4 ± 0.5	$0.049^{**,\ddagger}$; $0.102^{\dagger}$
Integration of force (N second)	1030 ± 310	924.2 ± 285.9	0.357^{*}	455 ± 139	$0.000^{**,\ddagger}$; $0.002^{\dagger,\ddagger}$

Group 1 = surgical trainees; Group 2 = orthopaedic residents; Group 3 = experienced arthroscopic surgeons; mean ± standard deviation; *p value for the comparison of Groups 1 and 2; **p value for the comparison of Groups 1 and 3; †p value for the comparison of Groups 2 and 3; ‡Significant difference.

Table 2. Results of Task 2

Parameter	Group 1 12	Group 2 12	p Value	Group 3 6	p Value
Time (seconds)	360 ± 0	339.6 ± 34.0	0.212^{*}	298.5 ± 75.7	$0.004^{**,\ddagger}$; $0.045^{\dagger,\ddagger}$
Path length of the scope (mm)	2257 ± 1066	4727 ± 1028	$0.014^{*,\ddagger}$	4894 ± 1717	$0.021^{**,\ddagger}$; $0.785^{\dagger}$
Velocity of the scope (mm/second)	9.3 ± 3.0	14.1 ± 3.7	$0.006^{*,\ddagger}$	16.7 ± 4.7	$0.001^{**,\ddagger}$; $0.174^{\dagger}$
Path length of the scissors (mm)	12845 ± 3032	10829 ± 1522	$0.042^{*,\ddagger}$	9661 ± 1848	$0.010^{**,\ddagger}$; $0.321^{\dagger}$
Velocity of the scissors (mm/second)	35.7 ± 8.4	32.0 ± 4.1	0.175^{*}	33.4 ± 6.1	0.496^{**}; $0.658^{\dagger}$
Peak force (N)	17.9 ± 6.6	26.3 ± 6.8	$0.004^{*,\ddagger}$	22.7 ± 6.0	0.154^{**}; $0.285^{\dagger}$
Average force (N)	4.0 ± 1.4	4.4 ± 1.0	0.394^{*}	4.4 ± 1.0	0.427^{**}; $0.921^{\dagger}$
Integration of force (N·second)	1433 ± 493	1497 ± 395	0.741^{*}	1372 ± 571	0.798^{**}; $0.600^{\dagger}$

Group 1 = surgical trainees; Group 2 = orthopaedic residents; Group 3 = experienced arthroscopic surgeons; mean ± standard deviation; *p value for the comparison of Groups 1 and 2; **p value for the comparison of Groups 1 and 3; †p value for the comparison of Groups 2 and 3; ‡Significant difference.

obtained better scores than the trainee group in adequacy of the resection (p = 0.003 for Group 1 vs 3; p = 0.029 for Group 1 vs 2) and smoothness of the margin (p = 0.011 for Group 1 vs 3; p = 0.004 for Group 1 vs 2), but we observed no difference in scores between the expert and resident groups (Fig. 3).

The expert group completed the procedures more quickly than the two less experienced groups in Task 1 (p = 0.000 for Group 1 vs 3; p = 0.000 for Group 2 vs 3) (Table 1) and Task 2 (p = 0.004 for Group 1 vs 3; p = 0.045 for Group 2 vs 3) (Table 2). We observed no difference in the mean time needed for each task between the resident and trainee groups.

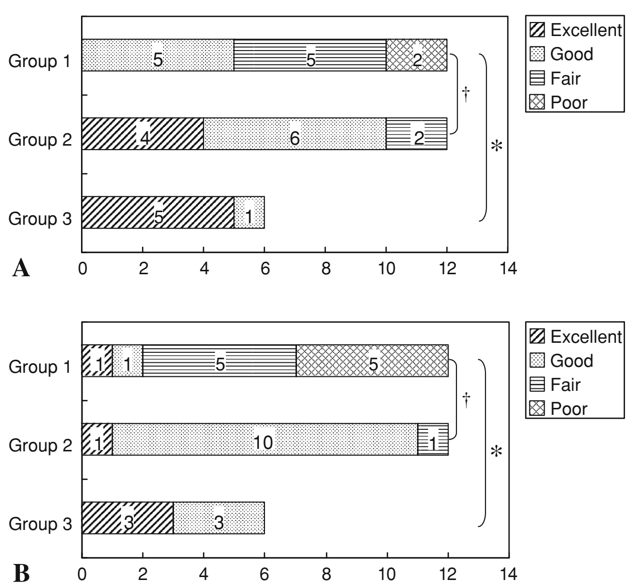

Fig. 3A–B (**A**) Scores for adequacy of the resection in Task 2, the meniscectomy task, are shown. The experienced surgeons (Group 3) and the orthopaedic residents (Group 2) showed better (*: p = 0.003; †: p = 0.029) performance than the surgical trainees (Group 1). (**B**) Scores for smoothness of the margin in Task 2 show Groups 2 and 3 obtained better (*: p = 0.011; †: p = 0.004) scores than Group 1.

In Task 1, the path length of the scope was shorter (p = 0.012) in the expert group than in the resident group and shorter (p = 0.043) in the resident group than in the trainee group, whereas the velocity of the scope was similar (p = 0.180) among the three groups. The path length of the probe was shorter (p = 0.001 for Group 1 vs 3; p = 0.015 for Group 2 vs 3) (Fig. 4A) and the velocity of the probe was faster (p = 0.003 for Group 1 vs 3; p = 0.040 for Group 2 vs 3) in the expert group than in the two less experienced groups (Table 1). In Task 2, the path lengths of the scope were longer (p = 0.021 for Group 1 vs 3; p = 0.014 for Group 1 vs 2) and the velocities of the scope were faster (p = 0.001 for Group 1 vs 3; p = 0.006 for Group 1 vs 2) in the expert and resident groups than in the trainee group (Fig. 4B) The path lengths of the scissors in the expert and resident groups were shorter (p = 0.010 for Group 1 vs 3; p = 0.042 for Group 1 vs 2) than that of the trainee group. The velocities of the scissors were similar (p = 0.389) among the three groups (Table 2).

The integrated force values applied by the expert group were lower (p = 0.000 for Group 1 vs 3; p = 0.002 for Group 2 vs 3) in Task 1 than those applied by the two less experienced groups (Table 1; Fig. 5). In Task 2, the peak force applied by the resident group was higher (p = 0.004) than that of the trainee group (Table 2). However, the average (p = 0.613) and integration (p = 0.862) of the force values were similar among the three groups (Table 2).

Discussion

Advances in arthroscopic surgical technique have revolutionized the diagnostic accuracy and therapeutic efficacy

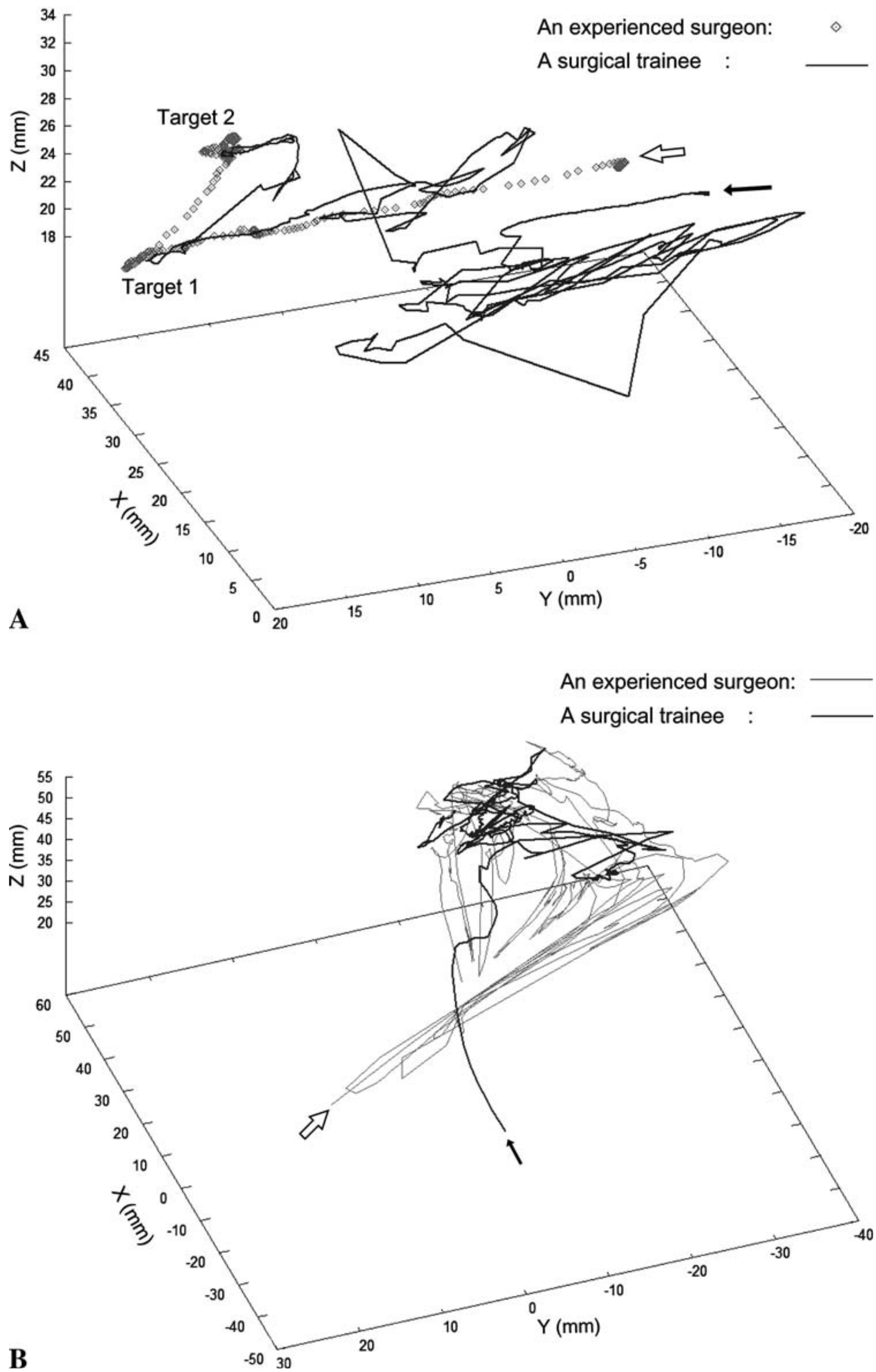

Fig. 4A–B (**A**) The probe tip trajectories of an experienced surgeon (dotted line) and a surgical trainee (full line) for Task 1 are shown. The probe path length of the experienced surgeon is considerably shorter and smoother than that of the trainee. (**B**) The scope tip trajectories of an experienced surgeon (thin line) and a surgical trainee (thick line) in Task 2 are shown. The experienced surgeon manipulated the scope more for better observation.

for intraarticular disorders [12, 17]. Although arthroscopic procedures demand highly developed psychomotor skills, the opportunity for orthopaedic trainees to learn those skills is limited and a means of objectively evaluating the skill levels of surgical trainees has not been established. This study was designed to clarify whether quantitative evaluation of arthroscopic surgical skills using scores, time to completion, instrument tip trajectory data, and force data was valid. We hypothesized more experienced surgeons therefore would obtain higher scores, complete tasks more

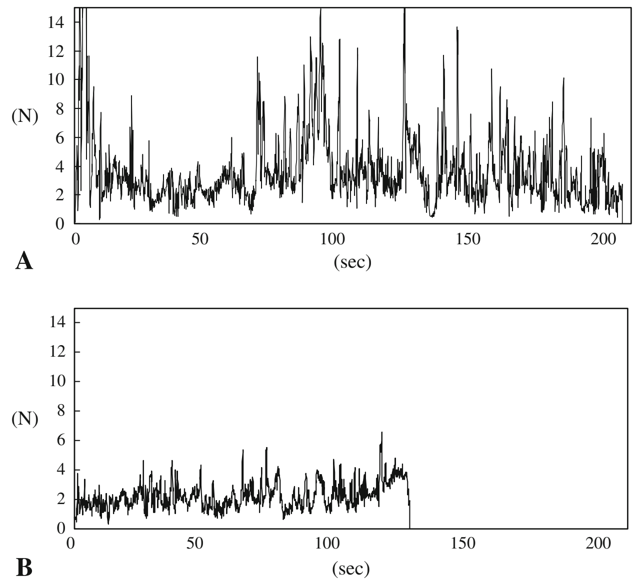

Fig. 5A–B (**A**) The time-series data of the output of a force sensor for a trainee are shown. Many large spikes are seen. (**B**) The force data of an experienced surgeon show time to completion is shorter and the forces are lower than those for the trainee.

quickly, and manipulate surgical devices more smoothly without loading any excessive forces on tissues in a simulated arthroscopic procedure than individuals with less experience, and this difference thus would validate the objective evaluation method.

One of the limitations of this study was simulated arthroscopic procedures were performed with Sawbones® physical knee models. Fresh cadavers would be more desirable to train and assess surgical skills of trainees outside the operating room, however, ethical restrictions and limited availability make use of cadavers difficult. To assess improvement of actual surgical skills of a person, a skill evaluation would be needed after he or she had gained a certain amount of real surgical experiences. However, the differences in motor performance depending on the real surgical experience suggest the evaluation method is valid and reliable. We had subjects perform only two kinds of tasks to assess their arthroscopic skills, although there are various situations and numerous techniques in arthroscopic surgery. We believe a simplified method would be more suitable for skill evaluation in surgical training than a complex and time-consuming one. A convenient means of discriminating surgical skills is needed in surgical education.

The score on Task 1 increased according to the surgical experience of the subjects. The score on Task 2 discriminated the more experienced two groups from the less experienced group. Previous studies suggest scoring surgical performance on simulated tasks is useful to assess surgical skills [7, 11, 15].

The experienced group performed both tasks more quickly than the two less experienced groups. Time to completion has been a popular parameter to evaluate surgical skills in arthroscopic and endoscopic training [2, 8, 12, 15, 18], although it cannot clarify the details of psychomotor skills in which the trainee lacks. These results of score and time data support the hypothesis that individuals with more experience in performing actual arthroscopic procedures also will perform better in simulated tasks.

An analysis of the trajectory data suggests experts manipulate the probe more smoothly and quickly than less experienced surgeons. Compared with experienced surgeons, the trainees had more unnecessary movements of the scissors. Similar results were reported in an evaluation study with a virtual reality simulator for shoulder arthroscopy. In that study, the probe path length of specialists was less than half as long as that of novices with no prior experience, and also shorter than that of residents with some experience [2]. Gomoll et al. also reported the probe velocity of specialists was almost double that of novices [2]. Another study with a shoulder arthroscopy simulator reported probe path lengths of experienced surgeons were shorter than those of trainees and residents [12]. A shorter path of the scope during a joint inspection and probing task, depending on surgical experience, suggests smoothness in handling the scope by more skillful surgeons. A validation study for a knee simulator suggested more experienced surgeons had substantially shorter scope path lengths during a loose body searching task, which required similar techniques as our joint inspection and probing task [9]. In Task 2, however, the positional data of the scope did not match this tendency. This suggests an increased trajectory of the scope does not mean more unnecessary movement in a task such as a meniscectomy, which demands different procedures from the joint inspection task. In fact, with Task 2, experienced surgeons tended to change their vantage points with freedom to make the meniscectomy work easier (Fig. 4B).

Force analysis is reportedly valuable to assess interference between surgical tools and tissues [13, 14, 19]. A previous study using a force sensor for an endoscopic sinus surgery training system proposed the peak as the instantaneous strong force, the average as the average force on the tissue, and the integration as the total force on the tissue during the tasks [19]. We found the integration of force by the two less experienced groups to be higher than values of experienced surgeons in the joint inspection and probing task. These forces were believed unnecessary, because the experienced surgeons used no such excessive forces. The use of excessive force might cause damage to the articular cartilage and soft tissues. However, force indices for Task 2 showed no differences between experienced surgeons and the two less experienced groups. The difficulty in distinguishing harmful from harmless contact would be the reason for this result. In one study, high force magnitudes were applied by novice surgeons in comparison to expert surgeons while performing tissue manipulation and vice versa in tasks involving tissue dissection [14]. Even useful manipulation of tools, such as repetitively cutting the meniscus, was detected as a harmful contact with the tissue, because the force sensor fixed beneath the joint model sensed the entire power loaded to the joint. A study evaluating a virtual reality simulator for shoulder arthroscopy also reported some of the useful probe contacts were potentially harmful collisions [15]. A force analysis system is required to improve the discrimination to resolve this problem.

It is important to assess the skill levels of surgical trainees. An objective evaluation system helps surgeons understand their degree of improvement and which technique they need to improve. We found score and time to task completion clearly discriminated the performance of the operators depending on their surgical experience. The path lengths of the probe and scissors by the experienced surgeons were shorter than those of the less experienced. The force analysis system detected excessive interference between the surgical tools and tissues for the joint inspection and probing task. Our data suggest this quantitative method of evaluating arthroscopic surgical skills using scores, time to completion, an electromagnetic motion tracking system, and a force sensor distinguish the level of surgical skill in an arthroscopic training system.

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